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TERNARY SUPERCONDUCTOR "NbTiTa" FOR HIGH FIELD SUPERFLUID MAGNETS

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Abstract - The possibility exists to obtain a higher 'Hc_2' upper critical field in the NbTi system which is normally limited by a spin-orbit coupling term. The introduction of scattering reduces this coupling. The spin-orbit scattering rate is proportional to Z^4 and therefore leads logically to the introduction of a high atomic number element which is more or less similar with respect to all of the other properties, i.e., Tc. Previous studies have shown Tantalum to be an excellent choice. The present work represents an attempt to obtain a high current density, high field ternary magnet conductor (Jc (10T, 2K, ρ_{eff} = 10^{-12} Ω-cm)) > 2000A/mm^2. This goal was met, but the conductor was clearly not optimized.

INTRODUCTION

In the last five to six years at Fermilab there has been a low level development program with the goal to fabricate high field, high current density superfluid helium accelerator magnets[1]. In conjunction and in collaboration with this program, there has been a metallurgical study to optimize the high field current density "Jc" of NbTiTa with its enhanced Hc_2. This study has been done by the University of Wisconsin group utilizing the expertise and production capabilities of Intermagnetics General and Teledyne Wah Chang Albany. The optimization study proceeded at UW using small experimental composites and then later material from a 25cm diameter extrusion. Simultaneously high homogeneity binary Nb46.5w/oTi composites were being optimized and fabricated thus providing a basis for a comparison. Three years ago, there arose a need for a high gradient quadrupole system for the new collision point in the Tevatron "Collider". One of the proposed lattices[2] required a quadrupole winding with a peak field > 9T. This provided the incentive to process one or two 30.5cm diameter billets of ternary alloy/copper composite into magnet conductor strand operating in superfluid helium at 1.8K.

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Historical Development of NbTiTa

The first studies by Suenaga and Ralls[3], of Hc_2 for the ternary composition of Nb, Ti, and Ta occurred in 1968-1972. The first attempts to obtain high "Jc" (magnet conductor) were done in 1978 by Segal, et. al[4]. A more detailed study of Hc_2 and "Tc" critical temperature was completed by Hawksworth and Larbalestier[5,6] in 1981. Then in 1982, our initial study of NbTiTa was undertaken starting with a not completely chemically homogeneous alloy, namely Nb41.5w/oTi15w/oTa. This study resulted in a conductor which was apparently limited by A) poor chemical homogeneity; B) large local ratio of Cu/NbTi; and C) intermetallics (possibly). Also during this same time frame, the Japanese groups of Watanabe, et.al.[7], and Wada, et.al.[8] fabricated some ternary composites. The "Jc" values (5T, 4.2K) were ~ 2000A/mm^2 range and "Jc" (8T, 4.2K) < 900A/mm^2 were obtained by these groups[9]. Then in 1986, with the increased fundamental understanding of "Jc" in the binary system for the Nb46.5w/oTi alloy and the need for a very high gradient lens in the Tevatron Collider, a high homogeneity "HiHo" alloy was fabricated utilizing the information acquired in the binary system studies and fabrication experience[10]. This diffusion barriered "HiHo" ternary alloy was fabricated into a 30.5cm diameter Cu composite billet.

The First NbTiTa Billet

A production run of ternary Nb41.5w/oTi 15w/oTa alloy was prepared. The amount of alloy made was ~ 50% more than necessary to fabricate a 25.4cm diameter copper composite billet at a Cu/NbTi ratio of 1.5/1. The alloy was forged, swaged, and finally drawn down to a rod size where

it could be cleaned, straightened, and cut into billet length rods. The rods were then placed in OFHC copper hex rods. These composites then could be stacked in a copper can with an electron beam welded end plate and nose cone, thus completing a 25.4cm billet prior to extrusion. The excess material was made into smaller multi-filament arrays; extruded, drawn, and precipitation heat treated. The cold work/heat treatment schedule for the larger billet was determined by the results obtained from these optimization studies of smaller arrays with respect to 5T and 8T.

The Second "HiHo" NbTiTa Billet

A production run of "HiHo" ternary Nb, 44.4w/oTi15.4w/oTa alloy was prepared. The alloy was wrapped with 0.76mm thick Nb foil at a 13.71cm diameter and placed in a copper can to become a billet. The assemblage of copper, alloy, and foil was subsequently compacted by hot isostatically pressing "HIPed" for void removal and then extruded. This composite was subsequently cold area reduced, shaved, and hexed to the proper copper to superconductor volume ratio for the desired stacking spacing. The composite hexes were then cleaned, straightened, and cut to length for extrusion. The hexes were then stacked into a copper can, end plate and nose cone, with an electron beam welded assembly. This 30.5cm diameter billet was "HIPed" and then extruded at as low a temperature as advisable. The extra material (the hex composite in excess of that required to fabricate the 30.5cm diameter billet for a 1.5/1 Cu/(superconductor + barrier)) was utilized in smaller multifilament arrays. These smaller arrays were then processed as previously done with various parameters (cold work and heat treatment) in order to optimize them with respect to Jc(5T, 4.2K) and Jc(8T, 4.2K) with emphasis on the latter.

Results

The first billet had the following properties: the alloy composition and variation was Nb41w/oTi, 15w/oTa with 3 to 4w/o variations globally. There were no local high Ta concentrations (>4w/o) as in previous production alloys. This composition and variation was verified with both X-ray photo and electron probe, as well as the wet chemistry analysis. The electron probe results were 41.5w/oTi and 15.0w/oTa with the remainder being Nb with concentration variation of the constituents being <4w/o. The production 25cm billet strand fabricated using a three heat treatment/cold work schedule similar to the binary optimum reached a critical current density of Jc (5T, 4.2K, ρeff = 10^{-14} ohm-m) = 2200A/mm^2 and 1230 A/mm^2 for Jc (8T, 4.2K, ρeff = 10^{-14} ohm-m). The best of the final strand had Jc (10T, 1.9K, ρeff = 10^{-14} ohm-m) = 1850A/mm^2. This represents a shift in the critical current curve of 4T between 4.2K to 1.9K as compared to the binary of 3T. This also represents a 50% improvement over earlier production results, but was 30% lower than the similar binary at 5T, 4.2K and slightly better at 10.0T, 2.0K than the best binary produced up to that time.

There were a series of short 'Tevatron' collared dipoles (minus the warm iron yoke) assembled and additionally clamped with large aluminum rings that were constructed during that time period[11]. The intent of this series of dipoles was to vary only one design parameter and fully characterize the magnet and it's subsequent performance. One of these dipoles was constructed using the ternary and several with binary conductor having slightly smaller or larger filaments which had similar critical currents at 4.2K. The binary dipole had a predicted ultimate 4.2K performance of 6200 Amps and attained a repeatable current of 6150 Amps (5.10T) at 4.25K. The ternary dipole had a predicted performance of 6300 Amps and attained a repeatable current of 6070 Amps (5.04T) at 4.25K. Subsequently, these dipoles were placed in a one atmosphere superfluid helium fixture and repeatedly quenched until a plateau current was determined. The binary dipole achieved the level predicted by the cable measurement with a plateau value of 7150 ± 20 Amps (5.93T) at 1.9K. The ternary dipole slightly surpassed the cable current value with a plateau value of 7560 ± 40 Amps (6.18T) at 1.9K. Therefore, the dipole's limit was slightly higher than the anticipated current due to increased Hc_2 alone.

There were several changes made for the second "HiHo" (high gradient quad) production billet, both in alloy and assembly. These were in part dictated by the increased knowledge of the binary obtained in the UW metallurgical characterization and fabrication studies[10,12,13] done in collaboration with the U.S. manufacturers for "SSC" Superconducting Super Collider cables. These changes were as follows: A) The percentage of Ti was increased by 3w/o (44.4w/o) to increase a rather sluggish optimization response of the previous alloy. This, in light of the subsequent data obtained for this alloy proved to be an error. The correct modification of the alloy would have been to increase the Ta content 2 to 5w/o and leave the Ti content alone. The subsequent Tc(H) measurements indicated that we reduced the critical temperature "Tc" by about 200mK and therefore had offset most of the increased Hc_2. B) The alloy was more homogenized (<2w/o global and local variations). This was one of the reasons the former alloy had not optimized as well as thought possible. C) The material had a diffusion barrier (Nb) added so that more aggressive heat treatments could be attempted without forming Ti-Cu intermetallics which distort the fine filament arrays during area reduction. D) The interfilament distance was decreased to minimize the geometry distortion of the filament array. E) The interfilament copper was extruded on

the Nb wrapped NbTiTa alloy. This step simplifies the fabrication process. F) A larger 30cm diameter composite extrusion billet was used. It was loaded with the composite rods in a cold worked state. This provided larger strain space in which to heat treat and optimize the final strand. There were ten binary billets processed so far with the same geometry and similar histories. All these have been fabricated for the high gradient lens system therefore providing an excellent basis for comparison to the ternary. The ternary billet prototype samples achieved Jc (5T, 4.2K) = 3100A/mm^2 and Jc (8T, 4.2K) = 1050A/mm^2 as compared to the binary Jc(5T, 4.2K) = 3150-3300A/mm^2 (See Figure 1) and Jc (8T, 4.2K) = 1380A/mm^2 (See Figure 2). The low temperature shift of the ternary "Jc" was not 4T as had been the previous 25cm billet experience; i.e., Jc (XT, 4.2K) ~ Jc ((X + 4)T, 2.0K). The present alloy results indicate that the corresponding increase is only ~ 3.4 - 3.2T. The Jc (10T, 1.9K) of the best "HiHo" sample (See Figure 3) measured to date is 2075A/mm^2. The bulk of the 30cm billet ternary conductor remains to be fabricated and measured. The cause of the lower Hc_2 for the "HiHo" alloy as compared to the earlier one appears to be the additional "Ti".

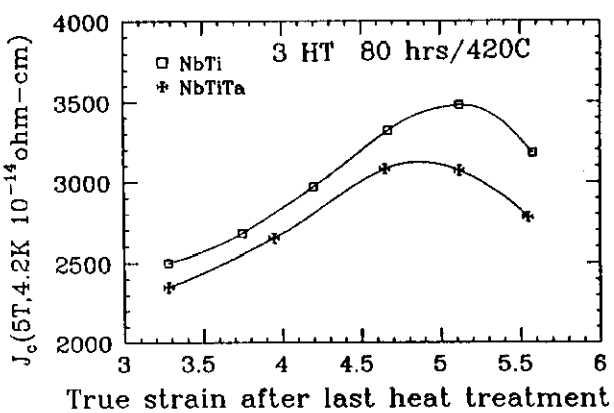

FIGURE 1 - THIS REPRESENTS THE OPTIMUM 'Jc' ACHIEVED TO DATE.

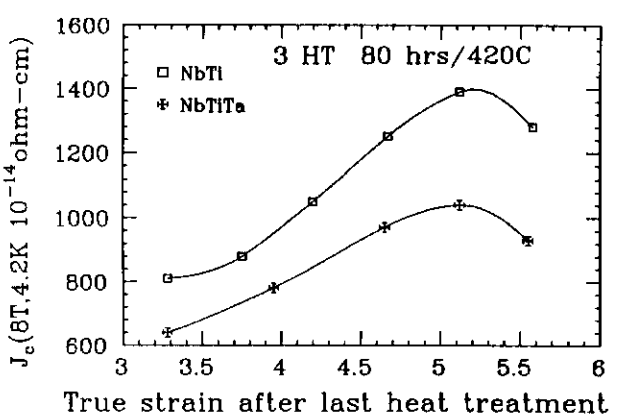

FIGURE 2 - THESE ARE THE CURVES CORRESPONDING TO DATA IN FIG. 1 AT 8T.

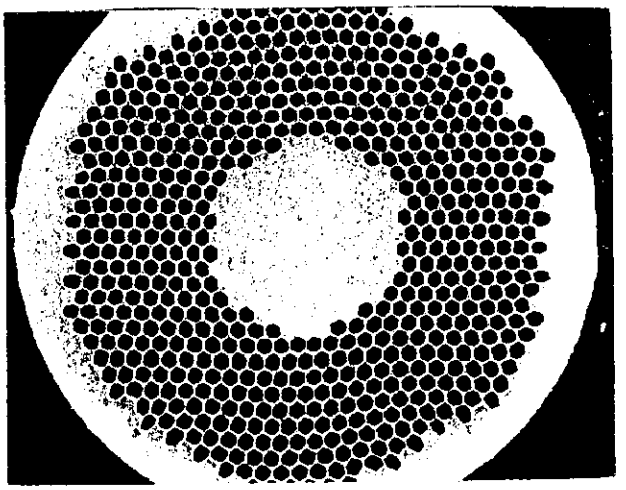

FIGURE 3 - PHOTOMICROGRAPH OF HIHO TERNARY BILLET CROSS SECTION.

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